where x_i is the ith data point,

$\bar{x}$ is the room or corner mean, and

n is the number of data points.

Appendix D contains tables of penetration losses for each building individually. The mean NLOS residential and high-rise building penetration losses are summarized in Table 3. The mean building penetration values for both LOS and NLOS are summarized in Table 4, where "All buildings" refers to the average of the high rise and residential measurements.

Table 3. Mean NLOS Penetration Losses

Building	912 MHz (dB)	1920 MHz (dB)	5990 MHz (dB)
Residential	7.7	11.6	16.1
High Rise	12.5	15.5	20.0

Table 4. Mean Penetration Losses for Both Transmission Paths

Frequency	Building	Loss (dB)
912 MHz	Residential	6.4
	High Rise	11.2
	All Buildings	8.2
1920 MHz	Residential	8.4
	High Rise	11.9
	All Buildings	9.8
5990 MHz	Residential	11.7
	High Rise	20.0
	All Buildings	14.1

We took NLOS and LOS measurements in each high-rise building. Time and accessibility restrictions made it impossible to measure all floors of all buildings. Receiver field strength deterioration at higher floor levels (due to distance and antenna pattern restrictions) made it impossible for us to measure floors above the fifteenth. Efforts were made to measure the same floors in each high-rise building in order to accommodate comparisons between the buildings.

The cumulative probability distribution function (CDF) shows the probability that penetration loss is less than or equal to the value of the penetration loss shown on the abscissa of the same graph. Figures 21 and 22 illustrate the CDFs for all seven residences and four high rises, respectively. Comparing the CDF's from all three frequencies, we see that, for both environments, the higher frequencies suffer greater penetration loss for NLOS paths. This is true consistently except in the high-rise buildings where the 1920-MHz probability is greater than the 912-MHz probability at small penetration losses (less than 12 dB) and less than the 5990-MHz probability at large penetration losses (greater than 40 dB).

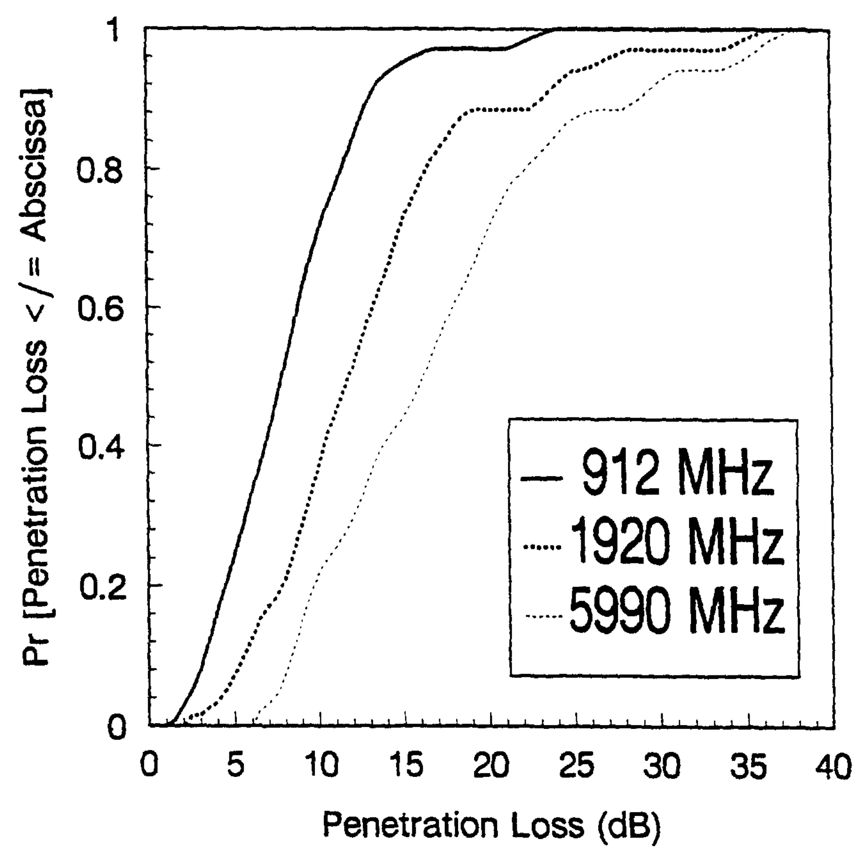

Figure 21. Cumulative probability distribution functions for NLOS residential penetration loss.

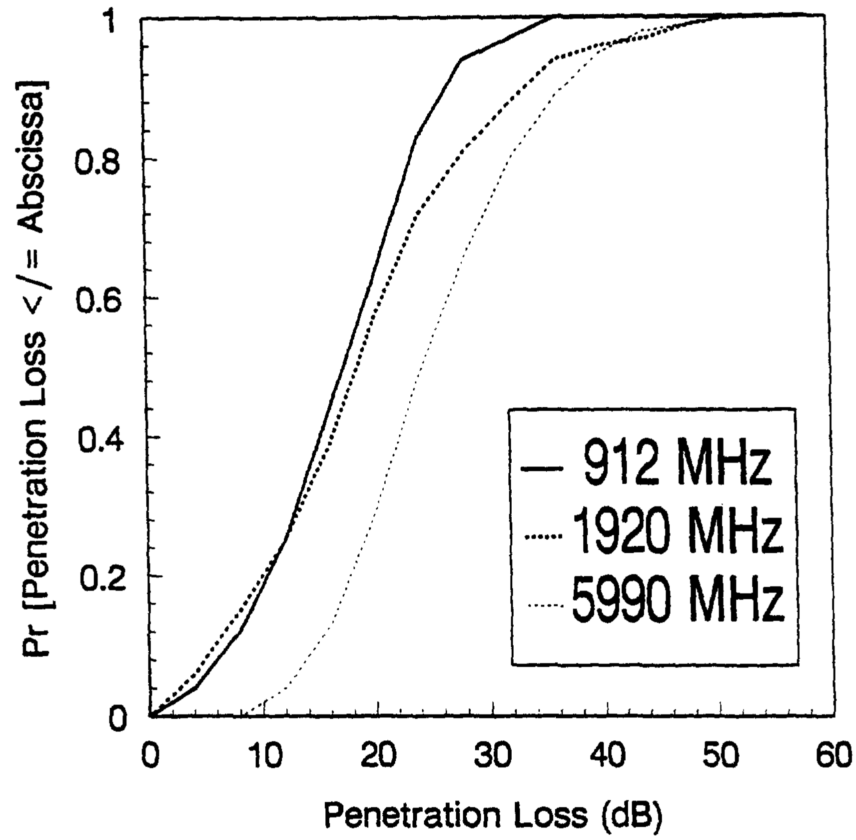

Figure 22. Cumulative probability density functions for NLOS high rise penetration loss.

4.2.1 Penetration Loss into Basements

The LOS building measurements showed greater penetration loss into basements than rooms at ground level. The difference is significant, as illustrated in Table 5. In fact, Cox, et al., recommend that "Because of the large average attenuation into the basement of the house, it does not appear reasonable to combine the basement attenuation statistics with the statistics for the rooms above ground level ([10])." It is, however, essential to incorporate a separate allowance for underground areas in the power requirement equation since PCS users may desire to operate their systems in basements and underground carparks.

Received signal strengths were so low in the underground NLOS high-rise measurements that we could not detect the deep fades at all frequencies. Therefore, the median value of the signal strength in these locations would have been optimistic and not valid for use in comparisons. For this reason, the NLOS underground penetration statistics are not included in this report.

Table 5. Differences Between Mean Ground Floor and Mean Basement LOS Penetration Loss

Frequency (MHz)	Residential (dB)	High Rise (dB)
912	8.7	20.8
1920	17.6	28.8
5990	19.9	34.8

4.2.2 Effects of Building Materials

Histograms of the mean NLOS residential building penetration losses and standard deviations are shown in Figures 23 and 24, respectively.[3] In Figure 24, the standard deviations are high. This is due to the fact that basement measurements have been included in the residential average. Basement penetration loss is significantly higher than the loss in all other rooms (see Table 5) and so causes the standard deviation to be larger.

Residence 1 was brick with wire mesh and plaster. Residence 2 was a tri-level with brick on the first floor and wood on the second. Residence 3 was all brick. Residence 4 was an all brick tri-level. Residence 5 was a two-story house with brick on the first floor, wood on the second floor, a full basement, and the entire house was wrapped with a metallic vapor barrier known as Thermoply®. Residence 6 was a two-story house with brick on the first floor, aluminum siding on the second, and a full basement. Residence 7 was a two-story house with brick on the first floor, wood on the second floor, and a full basement.

Based on the differences in residential building penetration between the three frequencies shown in Figure 23, building walls are frequency selective. This is reasonable because a building wall consists of a dielectric substance containing conducting objects. Such a structure may exhibit frequency-selective behavior, as has been documented by other researchers [1,11]. We also see that lower frequencies penetrate better than higher frequencies. Residence 3 has the highest penetration loss by 5 dB at 5990 MHz; the highest penetration loss by 0.5 dB at 1920 MHz; and the second to lowest penetration loss at 912 MHz. Residence 5 had the highest penetration loss by 3.2 dB at 912 MHz; and the 1920 and 5990 MHz penetration loss for this residence was less than 1.5 dB greater. Residence 2 had relatively low loss at 912 and 1920 MHz; yet "average" loss at 5990 MHz.

[3]Figures 23 and 24 include basement measurements.

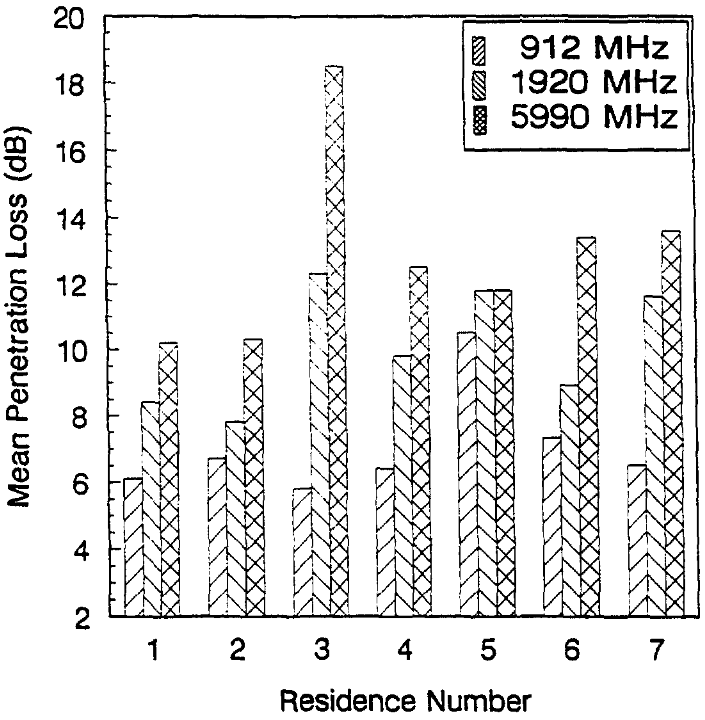

Figure 23. Mean NLOS residential penetration losses.

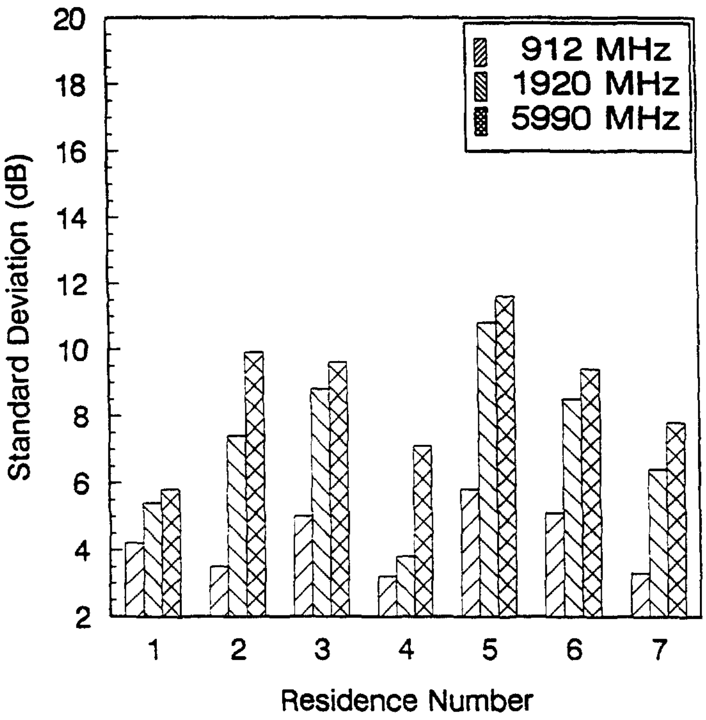

Figure 24. Standard deviations for NLOS residential penetration losses.

4.2.3 Effects of Multistory Buildings

Mean high-rise building penetration loss per floor is shown in Figures 25 through 28. High rises 1 and 4 have lower, more linear penetration losses than high rises 2 and 3. High rises 1 and 4 differ from high rises 2 and 3 in that they span entire city blocks, are newer construction, and contain large walls of glass. Walker reports that windows decrease penetration loss by 6 dB [12]. High rises 2 and 3 are of much older construction, are more closely surrounded by other buildings, have fewer windows, and have much more erratic penetration loss curves. High rise 2 has more windows and lower penetration loss than high rise 3. Figures 29 through 31 show penetration loss at 912, 1920 and 5990 MHz, respectively, for all high-rise buildings measured. The mean values for all data on each floor are indicated by "X's." The "least squares" straight line fit to these means, as calculated by GRAFTOOL™, is also shown on each plot. The slope and first-floor intercept of these lines are given in Table 6.

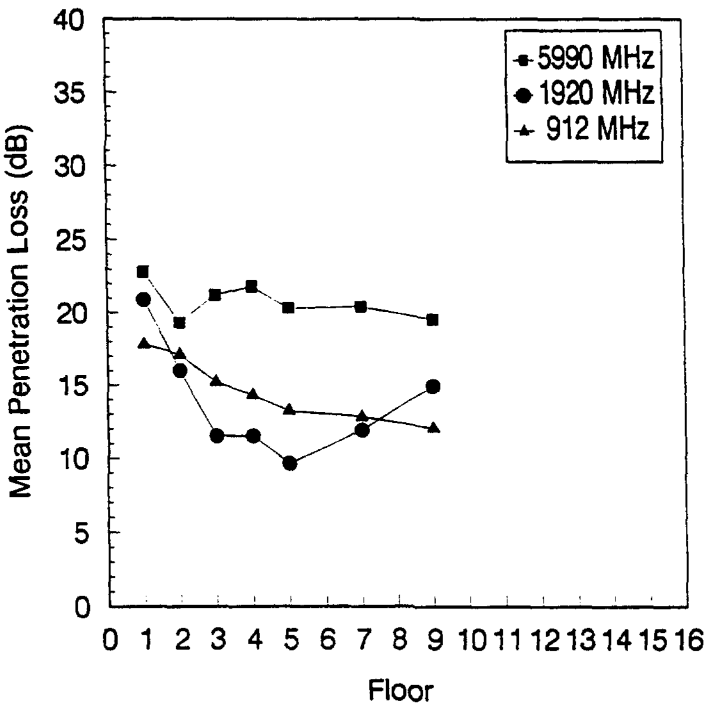

Figure 25. Mean NLOS building penetration losses for high rise 1.

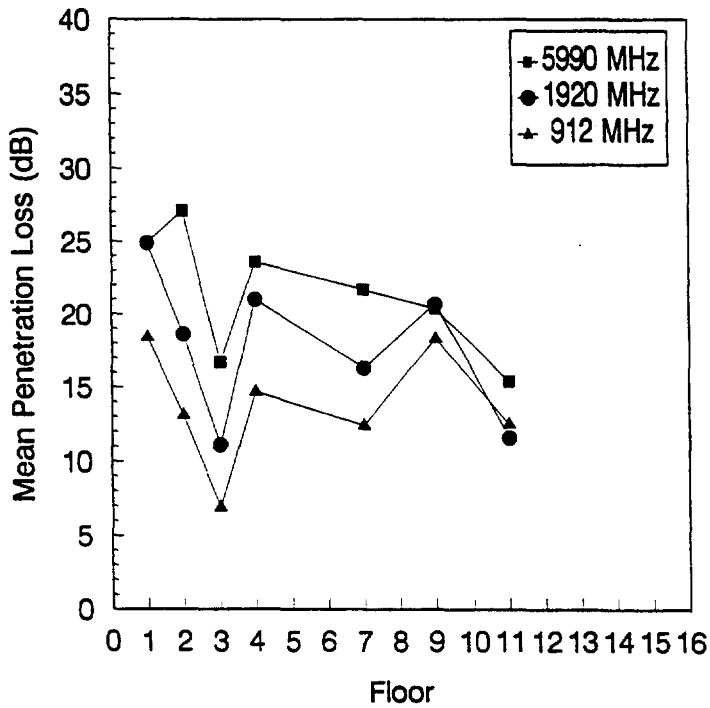

Figure 26. Mean NLOS building penetration losses for high rise 2.

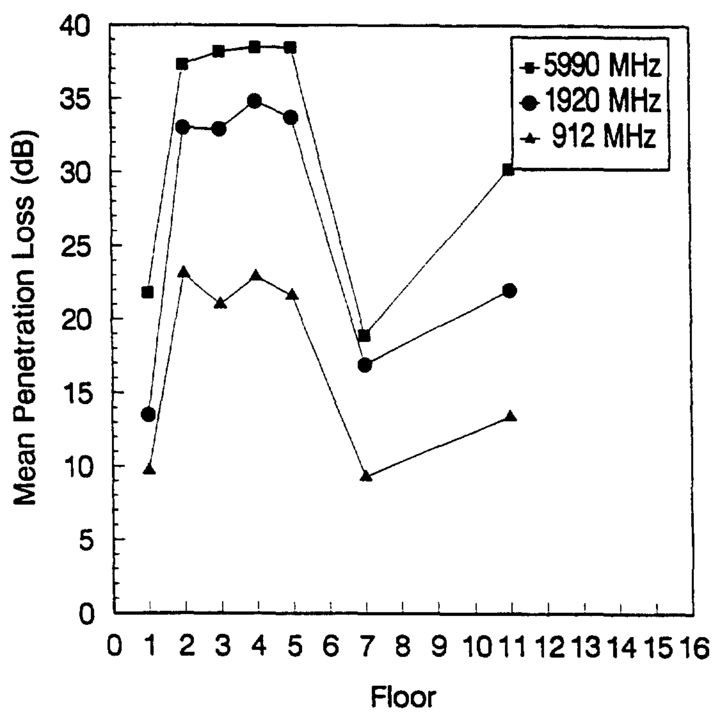

Figure 27. Mean NLOS building penetration losses for high rise 3.

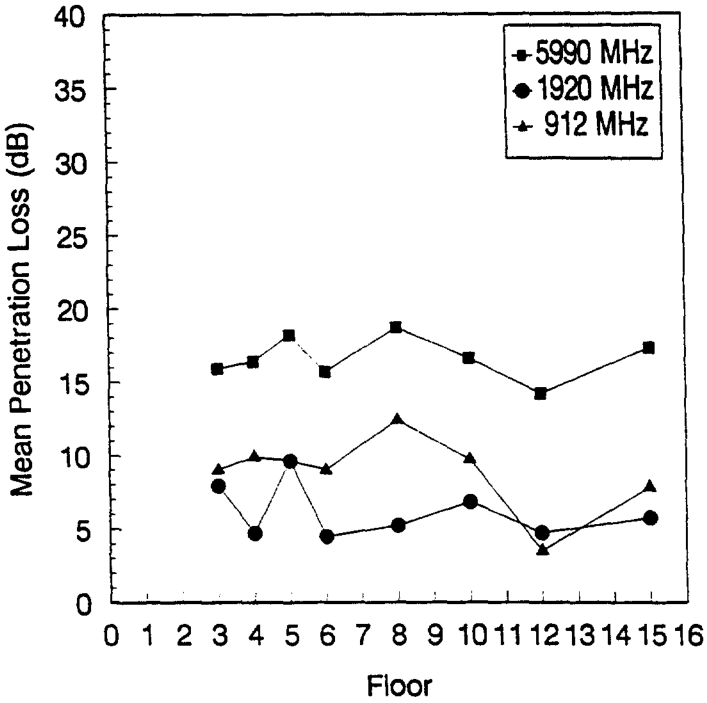

Figure 28. Mean NLOS building penetration losses for high rise 4.

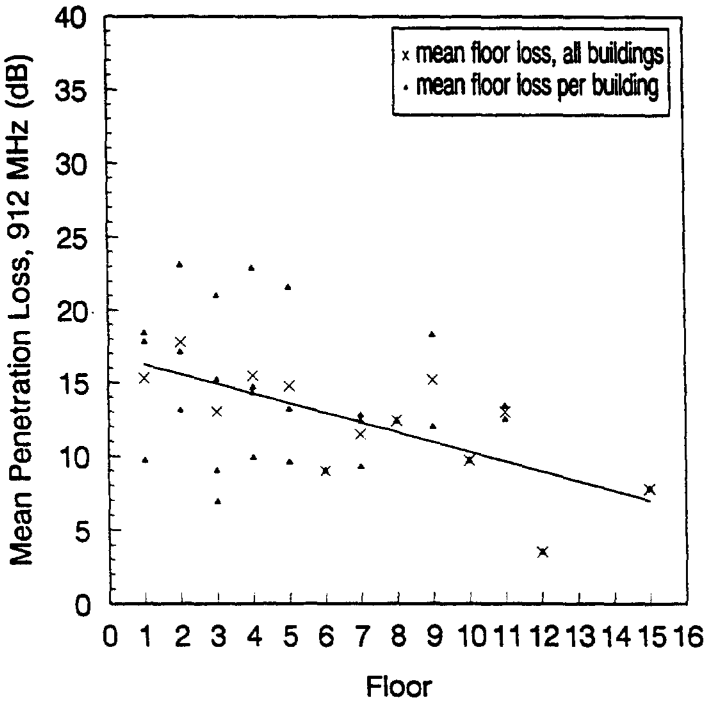

Figure 29. Mean NLOS high rise penetration loss at 912 MHz.

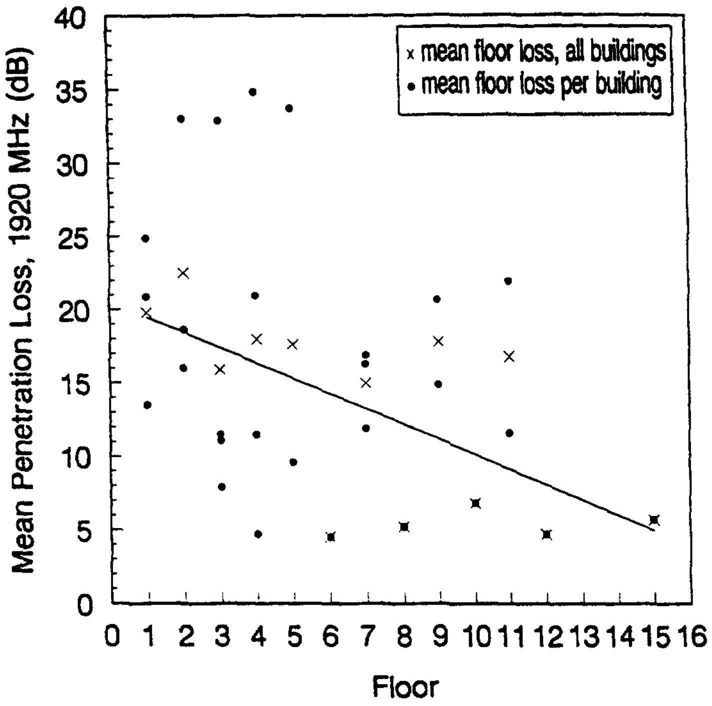

Figure 30. Mean NLOS high rise penetration loss at 1920 MHz.

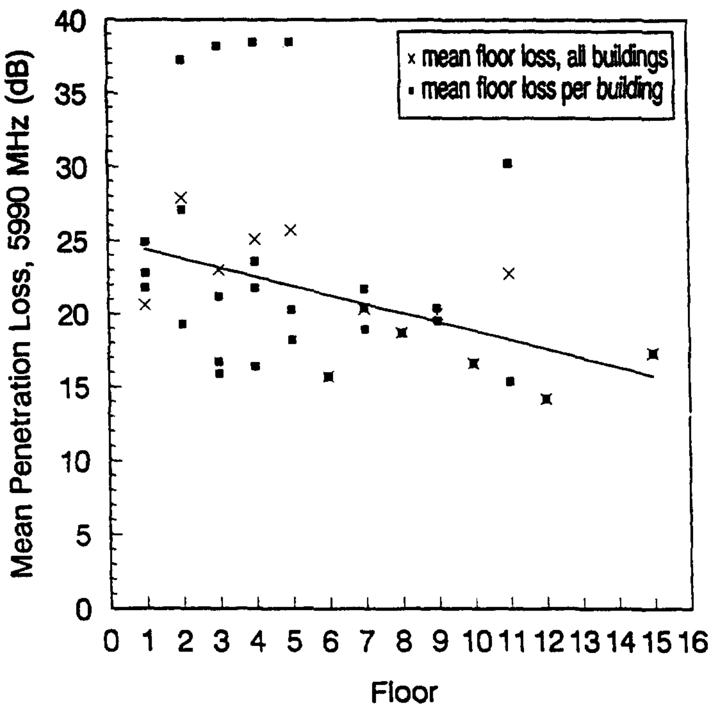

Figure 31. Mean NLOS high rise penetration loss at 5990 MHz.

Table 6. Slope and First Floor Intercept of "Least Squares" Line Fit to Mean Floor Penetration

	912 MHz	1920 MHz	5990 MHz
Slope	-0.66 dB/floor	-1.04 dB/floor	-0.62 dB/floor
Intercept	16.4 dB	19.6 dB	24.5 dB

4.2.4 Effects of Building Shadowing

Shadow loss is the attenuation of a signal due to diffraction around buildings. To calculate building shadowing, outdoor data were collected behind the buildings and subtracted from that collected in front of the buildings (LOS only). Average shadowing loss for each building is given in Table 7. If the building under test were the only building in the vicinity, we would expect the shadowing loss to increase with increasing building height and width, and with increasing frequency. The mean high-rise building shadowing loss is greater than the residential mean and the mean shadowing losses increase with increasing frequency. However, not all high-rise buildings have greater shadowing loss than all residences at the same frequency, and shadowing loss does not always increase with frequency even for the same building.

Table 7. Building Shadowing Losses

Site	912 MHz (dB)	1920 MHz (dB)	5990 MHz (dB)
Residence 1	7	4	1
Residence 2	9	10	8
Residence 3	9	19	26
Residence 6	15	19	21
Residence 7	15	17	23
High Rise 1	23	28	25
High Rise 2	35	41	46
High Rise 3	15	14	15
Residential Mean	11	14	16
High-Rise Mean	24	28	29
Building Mean	16	19	21

4.3 Slow Fading Analysis

The variation of the median signal strength about the path loss slope shown in Figure 17 is known as slow fading (also referred to as long-term fading or large-scale variations). Slow fading is typically caused by relatively small-scale variations in topography along the propagation path (i.e., construction materials used in the walls of buildings under test, and shadowing caused by buildings, trees or geographical variations). Knowledge of slow fading characteristics is critical in determining parameters such as required handoff speed and number of handoff requests. Slow fading effects are of particular concern because they generally cannot be eliminated using signal processing techniques such as equalization and coding.

Table 8 shows the standard deviation of the LOS data about the path loss slope. For the residences, standard deviation tends to increase with increasing frequency, whereas for the high rises, there is no increase between 1920 and 5990 MHz. The high-rise buildings show greater standard deviations than the residential buildings at 912 MHz, but this is not true for all buildings at 1920 and 5990 MHz. Some of the residences show higher standard deviations than high rise 1 at 1920, and most of the residences show higher standard deviation than high rise 1 at 5990 MHz. Referring to the environment around the buildings, high rise 1 is located in a relatively open area, with no vegetation in the propagation path. This indicates that any

Table 8. Standard Deviation of LOS Data about the Path Loss Slope

	Standard Deviation (dB)		
	912 MHz	1920 MHz	5990 MHz
Residence 1	6.3	7.4	7.7
Residence 2	6.6	7.5	7.1
Residence 3	7.1	8.9	10.3
Residence 4	6.6	7.9	9.1
Residence 5	7.4	9.8	10.4
Residence 6	7.2	10.2	10.8
Residence 7	7.6	8.7	9.9
High Rise 1	8.8	9.6	9.4
High Rise 2	9.4	11.1	11.0
High Rise 3	12.5	14.5	14.5
High Rise 4	12.1	14.3	13.0

obstruction between the transmitter and receiver is a factor in slow fading. High-rise building shadowing may be a significant factor in long-term fading at these frequencies, but is extremely area-dependent.

4.4 Fast Fading Analysis

The distribution of the fading about the local median is known as fast fading (also referred to as short-term fading or small-scale variations). It is caused by multipath reflections from surrounding objects. This type of fading is extremely rapid, with the possibility of very deep fades every half-wavelength. Figure 32 shows an example of our raw data. This figure shows fading measured with respect to time. The time elapsed for this sample was 10 s and the distance travelled was approximately 8 m. As seen here, fast fades occur more often, but for a shorter duration, at the higher frequency. Knowledge of fast fading characteristics is critical in determining adequate signal-to-noise ratios, and in designing optimum error-correction algorithms.

To calculate the fast fading distributions from the measured data, we subtracted each raw measured value from the mean of the room or corner. This removed the slow-fading component from the data, leaving only the fast-fading component for processing.

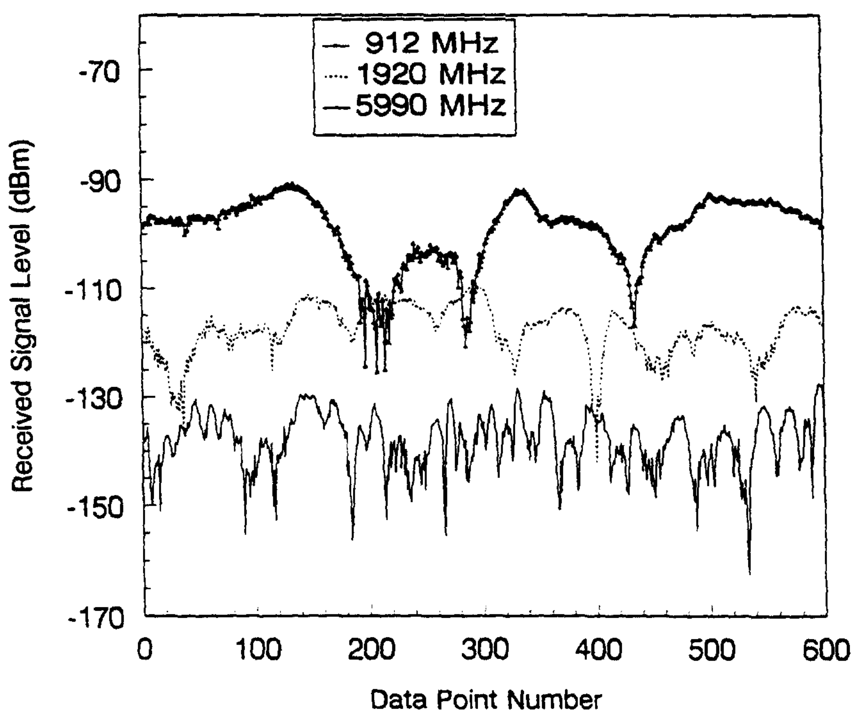

Figure 32. Example of raw data showing fast fading.

Figures 33 and 34 show fast fading cumulative probability distribution functions for residence 7, LOS, and high rise 3, NLOS, respectively. For both buildings, all three frequencies tend towards the same distribution shape. Fast fading is generally accepted to be Rayleigh distributed at distances of greater than 2 km, becoming less so and tending toward Rician distribution at closer proximities [13].

4.5 Correlation Analysis

Making simultaneous measurements at three frequencies allows a meaningful comparison of the three received signals. If a large correlation (i.e., close to 1.0) exists between any of these frequencies, then future measurements need only be collected at one frequency, and results could be extrapolated to another frequency or frequencies.

Figures 35, 36, and 37 compare the mean residential NLOS penetration losses between 912 and 1920 MHz, between 1920 and 5990 MHz, and between 912 and 5990 MHz, respectively. The graphs use one point per room and combine the results of seven houses. Figures 38, 39, and 40 compare the same parameters for the high-rise buildings, using one point per floor to combine the results of all four NLOS high-rise measurements. The regression line shown on the above graphs is the regression line as calculated by GRAFTOOL™ such that the deviation of the raw data points from the function is minimized. The correlation coefficients of the mean NLOS residential and high-rise building penetration losses are shown in Table 9.

Table 9. Correlation Coefficients of Linear Regression Between Frequencies

Frequencies (MHz)	Residential	High Rise
912 and 1920	.919	.928
912 and 5990	.763	.783
1920 and 5990	.942	.932

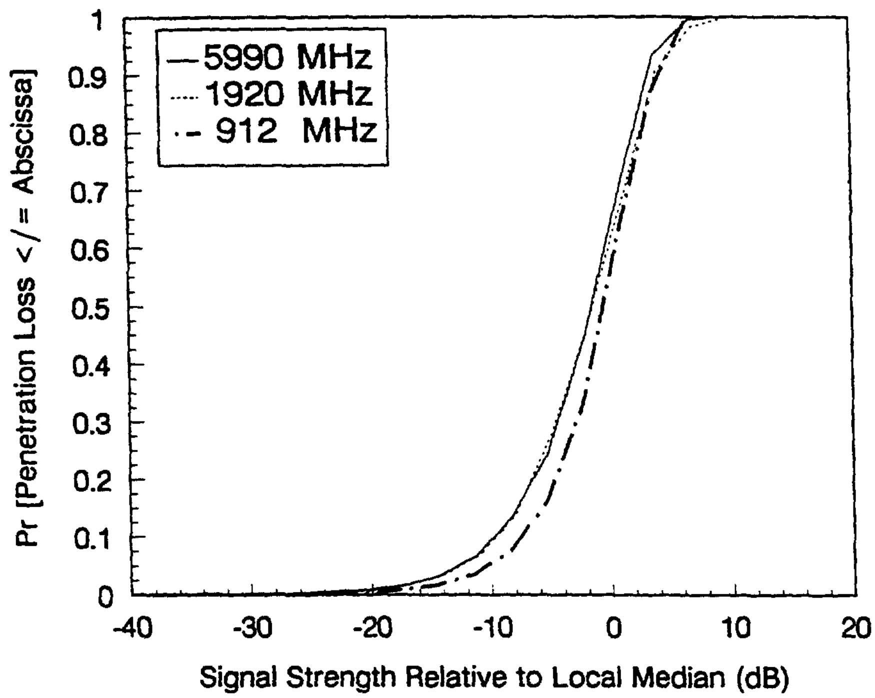

Figure 33. Cumulative probability functions for residential fast fading

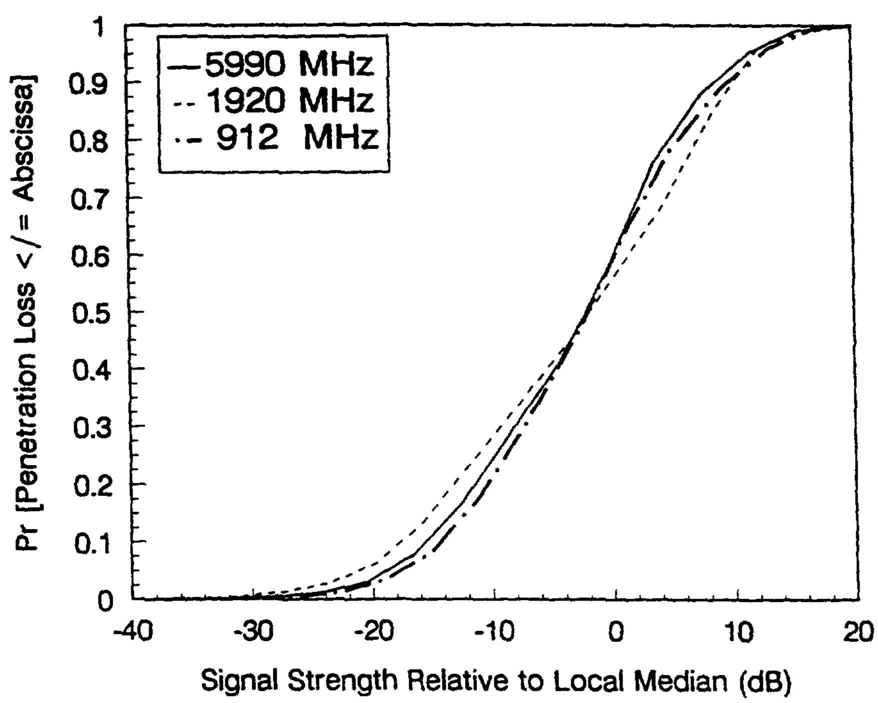

Figure 34. Cumulative probability distributions for high rise fast fading

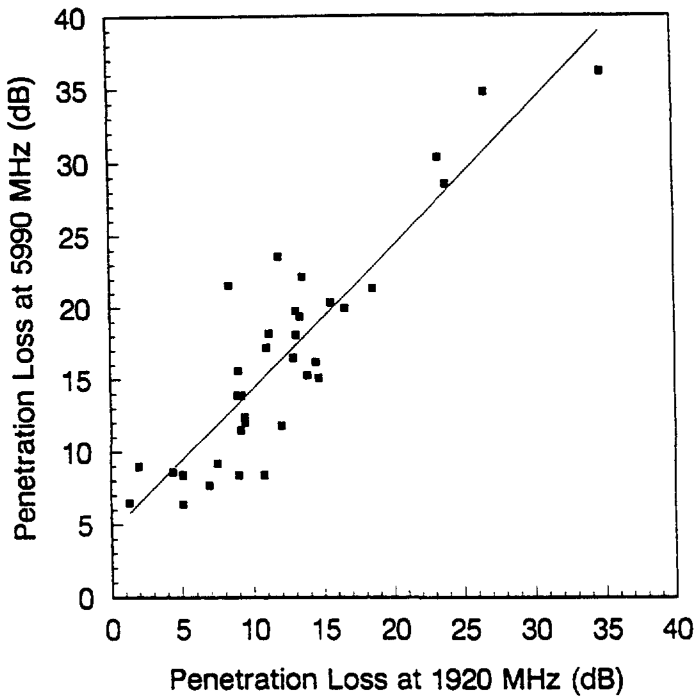

Figure 35. Comparison between 912 and 1920 MHz mean NLOS residential penetration losses.

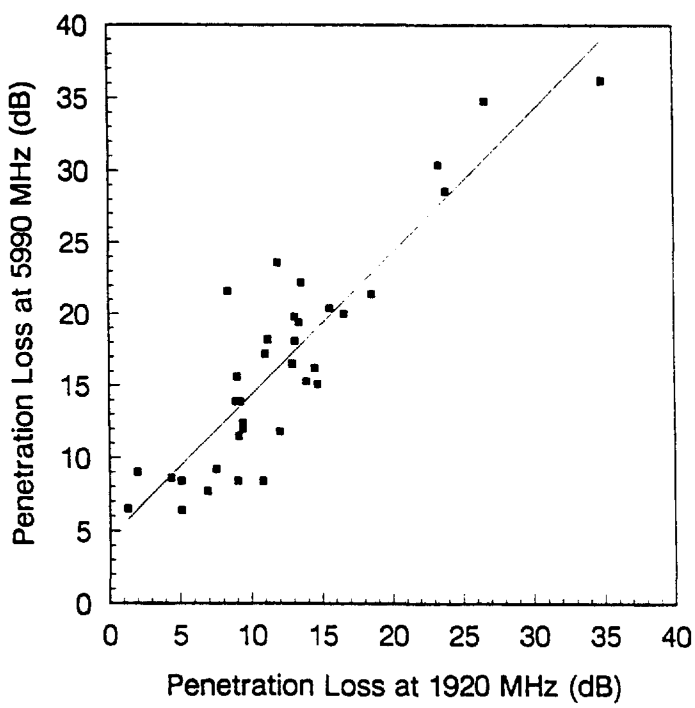

Figure 36. Comparison between 1920 and 5990 MHz mean NLOS residential penetration losses.

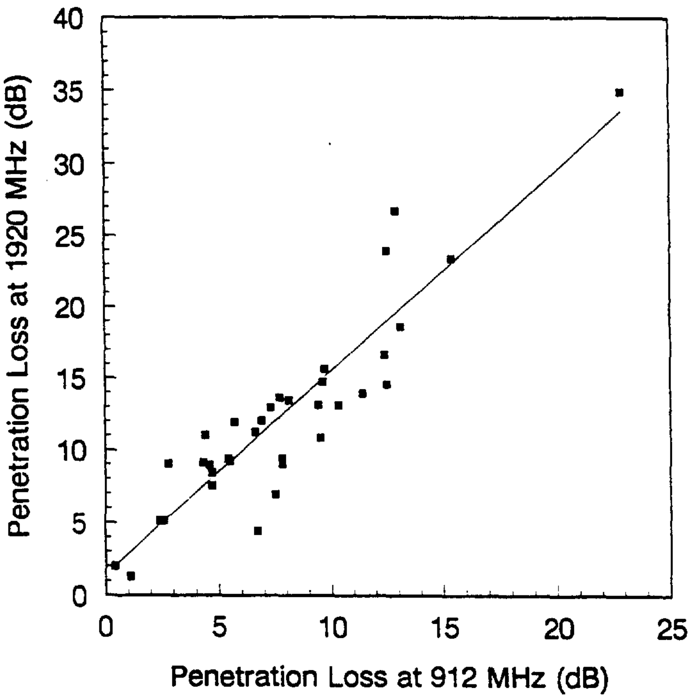

Figure 37. Comparison between 912 and 5990 MHz mean NLOS residential penetration losses.

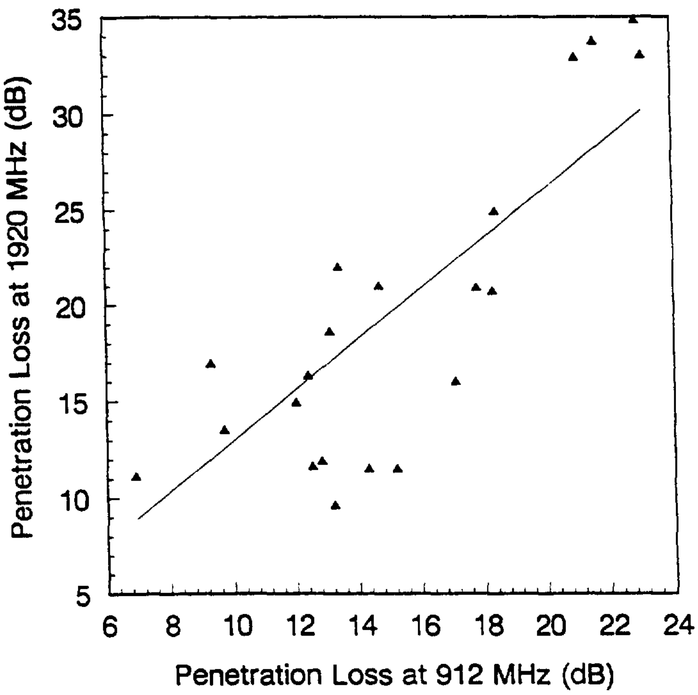

Figure 38. Comparison between 912 and 1920 MHz mean NLOS high rise penetration losses.

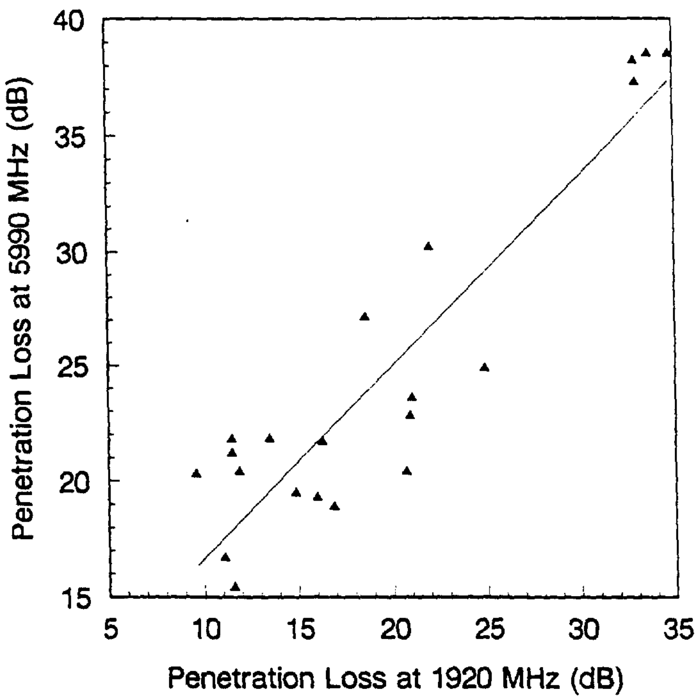

Figure 39. Comparison between 1920 and 5990 MHz mean NLOS high rise penetration losses.

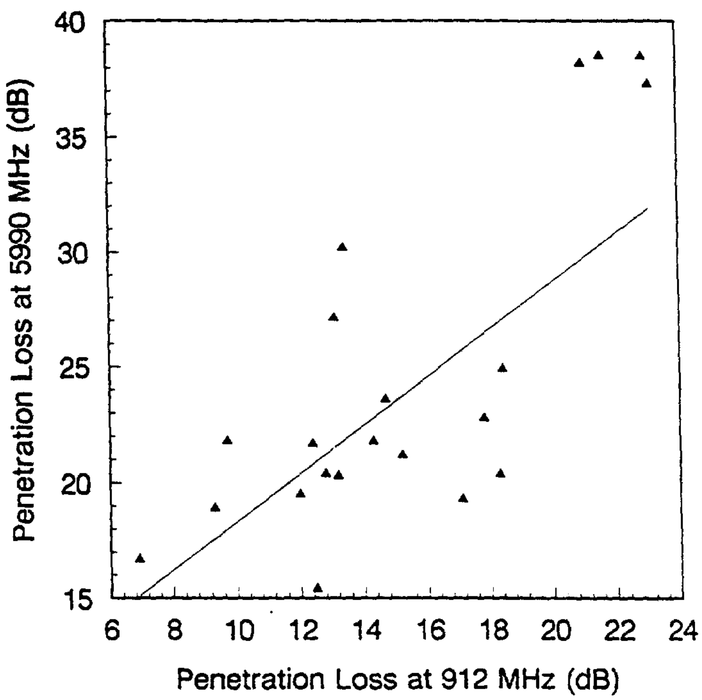

Figure 40. Comparison between 912 and 5990 MHz mean NLOS high rise penetration losses.

5. SUMMARY AND CONCLUSIONS

This report describes building penetration measurements conducted simultaneously at 912, 1920, and 5990 MHz. Eleven environments were measured, representing typical residential and high-rise buildings. Measurements were taken on all levels of the residential buildings, and seven or eight nonsequential levels of the high-rise buildings, up to a maximum of the fifteenth level. The measurement system consisted of a narrowband, fixed, outdoor transmitter and a mobile indoor receiver. The transmit and receive antennas were identical biconical, vertically polarized, omnidirectional antennas. From the data collected, we analyzed path loss distributions, penetration losses, building shadowing loss, loss into basements, slow fading, fast fading, and variations in loss due to frequency, building height, and building construction materials. A relationship between the data from the three frequencies was shown by way of correlation coefficients.

Path loss distributions
Although other researchers have described path loss into buildings as following a log-normal distribution [14, 15, 16], our data (see Appendix C) show no clear, consistent distribution. Although some of the distributions tend toward Gaussian or Rayleigh, many are bi-modal. The bi-modal distributions in the residences are caused by the fact that the basement path loss was significantly higher than the loss measured in the rest of the building. The bi-modal distributions seen in the high rise 2 and 3 LOS measurements are caused by the fact that only two corners of the building could be LOS to the transmitter, and therefore measurements were made in only these two corners.

Penetration loss
Penetration losses were calculated for each building from the path loss data collected. Penetration loss was found to vary with building location, construction material, frequency, and building level measured. The average penetration losses for all buildings was 8.2, 9.8, and 14.1 dB at 912, 1920, and 5990 MHz, respectively.

Penetration into basements
Signal penetration into basements was measured to be 8.7, 17.6, and 19.9 dB lower than penetration into the ground floor of the residences at 912, 1920, and 5990 MHz, respectively. LOS penetration into high-rise building basements was 20.8, 28.8, and 34.8 dB less than penetration at 912, 1920, and 5990 MHz, respectively. It is essential to incorporate a separate allowance for basements in the power requirement budget or to position additional transmitters in these areas if there is a desire to use PCS systems in basements and underground carparks.

Building construction variations
The high-rise building measurements consistently showed greater building penetration loss than the residential buildings. Presumably this is due to the use of steel frames and thicker walls of masonry or concrete in the high-rise buildings. We found the difference in median penetration loss at 912, 1920, and 5990 MHz to be 4.8, 3.5, and 8.3 dB greater, respectively, in the high-rise environment than in the residential environment.

Base antenna height considerations

The low base antenna height used for these measurements affected the path loss distribution and the frequency dependency of the penetration loss. When the base antenna height is low, penetration is mainly via walls and windows, and therefore the construction material of the building becomes more significant. This can create more variation in penetration loss at different frequencies, as the building materials can be frequency selective. The low base antenna height also leads to an increase in building shadowing, depending on the surrounding environs. This can create more variation in received signal level, but only affects penetration losses when the reference signal (ground level) experiences shadowing effects and the upper floors of the building under test do not. With a low base antenna height, the upper floors experienced similar shadowing effects, and so our measured penetration loss slopes (Figures 29-31) were less steep (see summary of building height dependency), and did not change after the fifth floor as found by other researchers. The low base antenna height does lead to increased shadowing effects and hence reduced signal levels inside the building, which will require either more base stations per city or increased transmitter power at each one.

Frequency dependency

The frequency variation of penetration loss appears to be largely dependent on building construction. For residential buildings, mean penetration losses increased as frequency increased, as found in [17]. However, not all the high-rise buildings followed this pattern. For most floors of high-rise buildings 1 and 4 (which had primarily glass walls), the 1920-MHz signal encountered less penetration loss than the 912-MHz signal. Tanis [18], and Davidson and Marturano [19] measured commercial building penetration losses that decreased as the frequency increased. Davidson and Marturano explained this apparent contradiction as a difference in building materials. Penetration into residences is primarily through the windows, walls and roof. Loss through these materials is relatively low and increases with increasing frequency. Both Tanis and Davidson and Marturano measured industrial buildings of reinforced concrete where the dominant penetration was through slots (windows and cracks). Loss through these materials decreases with increasing frequency. Allen, et al. [20] also found decreasing loss with increasing frequency for penetration through a metal building. Here, also, the dominant penetration is through slots (small windows, ducts and holes).

Building height dependency

For the high-rise buildings, NLOS penetration loss decreased 0.6 to 1 dB per floor as building floor level increased. Note that for all floors measured, the reference was always at street level. Most researchers [21, 22, 23, 24, 25, 26, 27, 28, 29] have observed that building penetration losses decrease 1 to 3 dB per floor for the first five or six floors of high-rise buildings. This difference in slope is probably due to the low transmitter height we used, causing the obstructions between transmitter and receiver to be more consistent, and the slope less steep. Transmitters placed on rooftops may have fewer obstructions to the upper floors of buildings than to the lower floors. Decreases in penetration loss are seen on the upper floors of high-rise buildings in urban environments [23], as opposed to high-rise buildings in suburban environments [12]. The penetration characteristics of buildings in urban areas depend highly on the surrounding structures, and are much harder to predict than for high-rise buildings in suburban environments. A couple of authors even noted penetration loss that increases at higher floor levels [11,12]. It is interesting to note that no matter what the pattern of the penetration loss versus floor level, all frequencies exhibit the same overall variation (Figures 25-28).

Building shadowing
The mean high-rise building shadowing loss is greater than the residential mean and the mean shadowing losses increase with increasing frequency. However, not all high-rise buildings have greater shadowing loss than all residences at the same frequency, and shadowing loss does not always increase with frequency even for the same building. This is due to the effects of multipath from the surrounding reflectors, such as buildings, geographical structures, vehicles, and vegetation; as well as the construction materials and contents of the building. Building shadowing loss is as dependent on the features of the area surrounding the building as it is on the building itself.

Slow fading analysis
Slow fading analysis reveals that any obstruction in the propagation path is a factor in long-term fading. Slow fading is frequency dependent and increases with increasing frequency in the residential building environment. In the high-rise environment, long-term fading is more difficult to analyze. Building shadowing loss may be a significant factor at these frequencies, but is extremely area-dependent.

Fast fading analysis
The fast fading characteristics of building penetration shows a tendency for all frequencies to have the same distribution shape, especially in the residential building. Deep fades occur more frequently as the frequency increases, but for a shorter duration.

Regression analysis
We observed strong linear correlations, greater than 0.90, between the penetration losses at 912 and 1920 MHz, and between 1920 and 5990 MHz. This opens the possibility of measuring building penetration loss at one frequency and extrapolating to find the penetration loss at other frequencies. The correlation between 912 and 5990 MHz, however, was less than 0.80, and so extrapolation between these two frequencies is not expected to be as accurate.

Implications of measurements
The ability to use the same mobile communications system in an uninterrupted manner both inside and outside buildings would be advantageous to PCS subscribers. If outdoor base stations can provide coverage to indoor users, handoff and its related difficulties are eliminated. Locating base stations on existing structures such as street or traffic lights has obvious economic advantages. The penetration loss measurements presented can be used to determine the feasibility of outdoor-to-indoor personal communication links. The cumulative distribution functions can provide link margin information to PCS designers. If building penetration losses of the magnitude presented in this paper can be tolerated by a PCS system, then there exists the possibility of using low-height base stations for transmission to indoor subscribers.

6. ACKNOWLEDGMENTS

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